Hypoxia in the Northern Gulf of Mexico: Past, Present and Future

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Abstract

The inner to mid-continental shelf from the Mississippi River westward to the upper Texas coast, is the site of the largest zone of hypoxic bottom water in the western Atlantic Ocean. The areal extent during mid-summer 1993–1995 (16,800 km^2, 16,300 km^2, and 18,200 km^2, respectively, of near bottom waters < 2 mg/l) rivals the largest hypoxic areas elsewhere in the world. Spatial and temporal variability in the distribution of hypoxia is, at least partially, related to the amplitude and phasing of the Mississippi River discharge. Freshwater fluxes dictate, along with climate, a strong seasonal pycnocline. Nutrients delivered by the Mississippi and Atchafalaya support high primary production, of which approximately 50 percent fluxes to the bottom. The high particulate organic carbon flux fuels hypoxia in the bottom waters below the seasonal pycnocline. Significant increases in riverine nutrient concentrations and loadings of nitrate and phosphorus and decreases in silicate have occurred this century, and accelerated since 1950. As a result of the nutrient alterations, the overall productivity of the ecosystem appears to have increased since the 1950's along with an increase in oxygen deficiency stress this century. Variable changes in nutrients and/or changes in freshwater fluxes will result in differing scenarios for distribution of hypoxia in the future.

Hypoxia is operationally defined as dissolved oxygen levels below 2 mg l^{-1}, or ppm, for the northern Gulf of Mexico, because that is the level below which trawlers usually do not capture any shrimp or demersal fish in their nets (Leming and Stuntz, 1984; Renaud, 1986). In this presentation, we outline the distribution and dynamics of hypoxia in the northern Gulf of Mexico, including present and historical conditions. We further detail historical conditions evident in the sedimentary record and use these retrospective analyses to predict future scenarios, including that of climate change. A more complete review of the subject is provided in Rabalais et al. (in press and in review).

Present Distribution

The inner to mid continental shelf of the northern Gulf of Mexico, from the Mississippi River birdfoot delta westward to the upper

Texas coast, is the site of the largest zone of hypoxic bottom water in the western Atlantic Ocean. The areal extent of this zone during mid-summer surveys of 1993–1995 (approx. 16,000 km^2 to 18,000 km^2; Rabalais et al., in review; Figure 7) rivals the largest hypoxic areas elsewhere in the world's coastal waters, namely the Baltic Sea and the northwestern shelf of the Black Sea.

Conditions during the Great Summer Flood of 1993 point to the importance of the river in the formation and persistence of hypoxia (see references in Dowgiallo, 1994). As a result of higher streamflow, especially in mid to late summer, there were:

- Lower than normal surface salinities
- Higher surface temperatures
- Increased stability in the coastal waters
- Increased overall loading of nutrients
- An order-of-magnitude higher than normal total phytoplankton counts
- A predicted greater flux of carbon to the seabed
- A significantly lower oxygen content of the lower water column
- An approximately two-fold increase in the areal extent of hypoxia with respect to the 1985–1992 mid summer averages, over an extensive area (Rabalais et al., 1994a).

Previous Years

Prior to 1993, the average areal extent of bottom water hypoxia in mid-summer was 8,000 to 9,000 km^2 (Rabalais et al., 1991). Distribution maps of mid-summer bottom water hypoxia since 1985 often show disjunct areas of low oxygen downfield of each of the river deltas (see 1992 in Figure 7). Other distributions are continuous from the Mississippi River delta to the upper Texas coast. When the 2 mg l^{-1} isopleths are not continuous along the shelf, however, the areas between are still undersaturated in oxygen with values usually below 4 mg l^{-1} and mostly below 3 mg l^{-1}.

Annual Cycle

Critically depressed dissolved oxygen concentrations occur below the pycnocline (Figure 8) from as early as late February through early October and nearly continuously from mid May through mid September. The importance of stratification and the physical structure of the water column in defining the distribution of hypoxia was discussed by Wiseman et al. (this volume). Hypoxic waters are distributed from shallow depths near shore (4 to 5 m) to as deep as 60-m water depth. The more typical depth distribution of hypoxic bottom waters, however, is between 5 and 30 m.

In March, April and May, hypoxia tends to be patchy and ephemeral; it is most widespread, persistent, and severe in June, July and August (Figure 9). The persistence of extensive and severe hypoxia into September and October depends primarily on the breakdown of the stratification structure by winds from either tropical storm activity or passage of cold fronts. Hypoxia is not just a bottom-hugging lens of water. It occurs well up into the water column; depending on depth of the water column, hypoxia may encompass from 10 percent to over 80 percent of the total water column.

Continuous time series show long periods of hypoxia and anoxia, a draw-down of hypoxia in the spring in response to respiration in the lower water column and at the seabed and sediment oxygen demand, vertical mixing and loss of stratification, response to winds (e.g., upwelling of deeper oxygenated waters), and, in other parts of the shelf, the influence of tidal advection (Rabalais et al., 1992; Rabalais et al., 1994b). While the 1995 areal extent of bottom water hypoxia was the largest ever recorded for the Louisiana shelf, its permanence over such an extent is not known. Based on monthly monitoring transects off Terrebonne Bay from 5-m to 30-m water depth and a continuously recording oxygen meter in 20-m water depth, the following can be said about the 1995 hypoxia season: Extensive low oxygen occurred as early as late May. During June and July oxygen levels were extremely low over large areas. Tropical storm activity re-aerated the water column during August, but low oxygen conditions again developed and low and extremely low values persisted into late September.

Proximal Causes

The relative magnitude in changes of freshwater discharge and nutrient flux from the Mississippi and Atchafalaya Rivers to the coastal ocean affects water column stability, surface water productivity, carbon flux, and oxygen cycling in the northern Gulf of Mexico.

High biological productivity in the immediate (320 gC m^{-2} yr^{-1}) and extended plume (290 gC m^{-2} yr^{-1}) of the Mississippi River is mediated by high nutrient inputs and regeneration, temperature and favorable light conditions (Sklar and Turner, 1981; Lohrenz et al., 1990). Spatial variation in primary production in a given period is related to salinity and the associated environmental and biological gradients (Lohrenz et al., 1990, 1994). There is a worldwide relationship between flux of dissolved inorganic nitrogen and primary production in coastal waters, and a similar relationship has been observed for the plume of the Mississippi River (Lohrenz et al., in review). The availability of dissolved silicate and its ratio to total inorganic nitrogen are also important in controlling the extent of diatom production and the composition of the diatom community with implications to carbon flux and control of oxygen depletion (Dortch and Whitledge, 1992; Nelson and Dortch, in press).

Particulate organic carbon flux to the lower water column is high in the extended plume over the inner shelf (Qureshi, 1995). The fraction of production exported is highly variable but averages about half of the estimated integrated primary productivity with statistically higher fluxes in the spring. A large proportion of the particulate organic carbon flux reaches the bottom incorporated in zooplankton fecal pellets (55 percent), but also as individual cells or in cell aggregates. Although Qureshi's data are limited to a single station in 20-m water depth off Terrebonne Bay for a 2-yr period, it appears that the amount of carbon fluxed is greater when the spring freshet of the river is higher. Also, the carbon fluxed via fecal pellets (during period of high flux) is sufficient to deplete the bottom water oxygen reserve in spring, thus creating hypoxic conditions that then prevail through the stratified summer period. When fluxes are lower (e.g., in lower flow years, or in summer) the oxygen depletion rates for these fluxes are close to the calculated oxygen depletion rate.

On a seasonal time scale, productivity is most influenced by Mississippi River flow and nutrient flux to the system. Long-term mean seasonal variations in net productivity at a station in 20-m water depth off Terrebonne Bay are coherent with the dynamics of freshwater discharge (Justic´ et al., 1993). The surface layer shows an oxygen surplus during February-July, the maximum occurs in April and May and coincides with the maximum flow of the Mississippi River. The bottom layer exhibits an oxygen deficit through the year, but reaches its highest value in July (coincident with maximum pycnocline strength). The correlation between the Mississippi River flow and surface oxygen surplus peaks at a time-lag of one month, and the strongest correlation for bottom water oxygen deficit is for a time-lag of two months. The oxygen surplus is also a good indicator of excess organic matter derived from primary production which can be redistributed within the system [which follows Qureshi's (1995) results].

A similar 2-month lag of bottom water hypoxia following peak Atchafalaya River flow was observed by Pokryfki and Randall (1987) for the southwestern Louisiana shelf for data from the early 1980's. Low surface salinities lagged one month behind peak river flow. Their model did not incorporate any biological processes, which with additional lags would increase the accuracy of their predicted low oxygen periods. The physics, geological setting and important biological parameters, such as light fields and nutrient flux, differ on the southwestern Louisiana shelf from that of the southeastern shelf. It is also not clear how the effluents of the Mississippi River and the Atchafalaya River merge to produce the physical structure of the area. Wiseman and Kelly (1994) demonstrated that salinity signals from both river discharges were detectable off the Calcasieu estuary. However, similar biological processes occur on the southwestern shelf so that a large area of hypoxic bottom waters to the west of the Atchafalaya River appears to form each season.

Historical Data

Our systematic surveys began in 1985. Extensive shelfwide distributions of hypoxia occurred each summer of those years, with the exception of 1988 (a record low flow year for mid-summer; hypoxia developed as usual in the spring, but not maintained in the summer). Prior to 1985, the data are mostly ancillary to other studies, thus do not form a complete survey, either temporally or spatially. There were some directed studies in the early 1970's (Ragan et al., 1978; Turner and Allen, 1982).

The mention of low oxygen conditions from the mid 1930's in the Conseil Permanent International pour l'Exploration de la Mer Bulletin Hydrographique for 1935 were identified in Hedgpeth's Treatise on Marine Ecology and Paleoecology (Brongersma-Sanders, 1957; Richards, 1957) as records from the oxygen minimum zone of deeper waters (e.g., 400–500 m deep) and several authors have shown that there is no continuation of the oxygen minimum zone with the hypoxia on the inner to mid continental shelf (Pokryfki and Randall, 1987; Rabalais et al., 1991).

Hypoxia was first recorded in the early 1970's off Barataria and Terrebonne / Timbalier Bays as part of environmental assessments of oil production and transportation development studies (the Offshore Ecology Investigation, OEI, and the Louisiana Offshore Oil Port, LOOP). Ragan et al. (1978) and Turner and Allen (1982) followed up with studies in 1975 and 1976 along the Louisiana coast and documented low oxygen conditions over most of the areas they studied in the warmer months. Environmental assessments for brine disposal areas and further studies of oil and gas production areas revealed low oxygen conditions in most inner shelf areas studied in mid-summer.

Hypoxia along the upper Texas coast is usually an extension of the larger hypoxic zone off the Louisiana coast, although isolated areas may be found (e.g., Big Hill area and Bryan Mound areas, but may be an artifact of the sampling). Most instances of hypoxia along the Texas coast are infrequent, short-lived, and limited in extent. There are no records of hypoxia below the Freeport, Texas area (with the exception of one record at SEADOCK off the Brazos River)

(Rabalais, 1992). There are very few systematic surveys for this area.

There are reports of hypoxia off Mississippi Sound during high stages of the Mississippi River; also reports off Mobile Bay in bathymetric low areas. There are usually more reports in flood years (especially 1993, related to the high flow of the river late in summer and movement of the waters to the east of the delta by the persistent southerly and southwesterly winds).

Prior to the 1970's, there is some anecdotal information from shrimp trawlers in the 1950's–1960's of low or no catches, of "dead" or "red" water, but no systematic analysis of these records.

Changes in Nutrient Loadings

These results are outlined in papers by Turner and Rabalais (1991, 1994a,b), Justic´ et al. (1994, 1995a,b) and Turner et al. (this volume):

- Nutrient concentrations and loadings have changed dramatically this century and accelerated since the 1950s.
- Concentrations of dissolved N and P have doubled, and Si have decreased by 50 percent.
- Nutrient composition in river and adjacent Gulf waters has shifted towards ratios closer to the Redfield ratio and more balanced than previously.
- These changes are closely related to N and P fertilizer applications in the watershed.
- Offshore nutrient compositions shifted along with potential and probable nutrient limitations.
- Water quality changes are specific to changes in nutrients. Freshwater inflow has remained fairly stable, although there is a slight increase in total flow in the last two decades due to an increase in Atchafalaya River flow (Bratkovich et al., 1994).

Ecosystem Changes

Long-term changes in the severity and extent of hypoxia cannot be assessed directly, because systematic sampling of bottom water dissolved oxygen concentrations did not begin until 1985. Therefore, biological, mineral or chemical indicators of eutrophication and/or hypoxia preserved in sediments, where accumulation rates record historical changes, provide clues to prior hydrographic and biological conditions. Similar analyses have proven useful in the Great Lakes and Chesapeake Bay and were done for the Mississippi River bight.

An analysis of long-term data sets and diatom, foraminifera, and carbon accumulation in sediments supports the inference of increased eutrophication and hypoxia in the Mississippi River delta bight primarily because of changes in nitrogen loadings. These results are outlined in Rabalais et al. (in press).

The work of Eadie et al. (1994) demonstrated from two cores in the Mississippi River delta bight an increased accumulation of marine-origin carbon in the last 100 years, consistent with changes in productivity beginning in the mid-1950's when benthic foraminiferans rapidly became isotopically lighter. Beginning in the mid-1960's, the accumulation of organic matter, organic $d^{13}C$ and $d^{15}N$ showed large changes in a direction consistent with increased productivity. The latter period coincided with a doubling of the load of nitrates in the Mississippi River outflow which leveled off in the 1980's. Increased carbon accumulation was also calculated from BSi (a surrogate for diatom production) accumulation rates in Turner and Rabalais (1994a).

Diatom-based productivity and BSi accumulation provide other lines of evidence of increased productivity. In spite of a probable decrease in Si availability, the overall productivity of the ecosystem appears to have increased this century. This is evidence by:

- Equal or greater net silicate-based phytoplankton community uptake of silica in the mixing zone, compared to the 1950s (Turner and Rabalais, 1994b)

- Greater accumulation rates of biogenic silica (BSi) in sediments beneath the plume, but not further away, and in agreement with results found in freshwater systems (Turner and Rabalais , 1994a). The increased BSi in Mississippi River bight sediments parallels increased N loading to the system and is direct evidence for the effects of eutrophication on the shelf adjacent to the Mississippi River.

Finally, an analysis of benthic foraminiferans in offshore sediments indicates an increase in oxygen deficiency stress this century, with a dramatic increase since the 1940's–1950's. Several cores from areas of varying levels of frequency of hypoxia (in the Mississippi River delta bight) were examined by Barun Sen Gupta and colleagues (in Rabalais et al. in press, Sen Gupta et al. in press). They documented a progressive overall rise in oxygen stress (in duration or intensity) with these indicators: (1) an increase in the ratio of *Ammonium* to *Elphidium*, (2) a decrease in species not tolerant of oxygen stress, and (3) an increase in species tolerant of low oxygen stress. These changes were coincident with the rise in river-borne nutrients and accumulation of biogenic silica.

Increased bottom-water hypoxia could result from increased organic loading to the seabed and/or shifts in material flux (quantity and quality) to the lower water column. Oxygen-depleted bottom waters in the coastal ocean are found worldwide. The incidence and extent of such areas in coastal waters is apparently increasing and related to anthropogenic nutrient loadings in rivers (Diaz and Rosenberg in press). The patterns of worsening water quality in coastal waters adjacent to the terminus of major rivers undergoing nutrient flux or water quality alterations are consistent with the conditions identified for the Mississippi River.

Future Scenarios

The enormity of effecting environmental change on the continental shelf at the terminus of the Mississippi River might seem insurmountable for a watershed that includes 41 percent of the conterminous U.S., encompasses parts of many states and innumerable other regulatory or legislative boundaries, and integrates centuries of landscape changes within the watershed and alterations of the Mississippi River proper. Still, effective policy for managing and restoring ecosystems can be accomplished, especially if the results of scientific inquiry are integrated into the process.

Rabalais et al. (in press) made several predictions of ecosystem response given certain changes in nutrients (Figure 10):

If Si increases, and N remains the same; overall N limitations would be similar to present, but Si will no longer be limiting. This would result in increased BSi and carbon accumulation in sediments, and an increase in the extent and severity of hypoxia.

If Si increases, N increases, and Si and N remain in balance; no N or Si limitations. The result would be greatly increased BSi and carbon accumulation and substantial increase in severity and extent of hypoxia. This is the result demonstrated in the 1993 flood and in a doubled CO_2 climate scenario.

If Si increases, N decreases to 1950s values; N would return to the limiting nutrient status, and although Si would be in abundant supply, the system would be restricted by N supplies and hypoxia would decrease.

To reach the 1950s levels of dissolved N would require a 40-50 percent reduction in the current loadings that exit the Mississippi River delta. Identification of sources of nutrients within the Mississippi River watershed that eventually reach the Gulf of Mexico should lead to avenues of management. While the results of changes in nutrient delivery to the northern Gulf of Mexico are clear, the delineation of the sources and their fate and transformation as they are delivered to the Gulf is not complete (however see Alexander et al., Antweiler, and Goolsby in this volume). It is important to understand which agricultural practices, water treatment practices, water quality regulations, consumer preferences, and economic incentives and disincentives result in the amount of dissolved N, P and Si in the Mississippi river. Management alternatives directed at water issues within the Mississippi River watershed may have unintended and contrasting impacts on the coastal waters of the northern Gulf of Mexico.

Howarth et al. (in review) modeled N loadings to the North Atlantic Ocean and treated the Mississippi River watershed as a unit. Sewage input of N is 9 percent of the total inputs from the Mississippi River to the North Atlantic Ocean. Of four anthropogenic sources, application of fertilizer contributes the greatest input of N (54 percent), followed by fixation by leguminous crops (31 percent) and atmospheric deposition of NOy (15 percent). The ratio of current river N export to "pristine" river N export for the Mississippi River ranges from a 4.8 to 7.4 fold increase. The Howarth et al. model points to a reduction in nonpoint sources, agricultural, direct or indirect, as the key to nutrient pollution control.

There is a direct connection between river nutrient loading and the hypoxic zones on the Louisiana shelf. River diversions aimed at wetland restoration might be considered a possible management tool to decrease nutrient loading to the offshore waters and thereby raise oxygen concentrations in offshore bottom waters. However, the amounts of river water to be diverted are so small relative to the size of the total discharge that river diversions will have an insignificant effect on the size, frequency and duration of oxygen depletion within bottom waters offshore. For example, river diversions are currently operating, or being planned, to bring large quantities of water from the Mississippi River into adjacent estuaries of Barataria Bay, Breton Sound, and Lake Pontchartrain. U.S. Army Corps of Engineers estimated maximum flow for:

Davis Pond
10,650 cfs (likely to move west from delta)
Caernarvon
8,000 cfs (to east)
Bonnet Carré
30,000 cfs (to east)
Total
48,650 cfs (equal 10 percent of average flow 4.6×10^5 cfs, 1954–1988).

However, these diversions will function perhaps one or two months of the year on variable schedules for either fresh water or sediment delivery, and the flows listed above are maximal. The total diverted discharge will be significantly less than 10 percent of the total discharge volume for the year. Further, diversions of river waters to the east of the Mississippi River delta may aggravate the limited and ephemeral conditions of hypoxia there or further flow through the Atchafalaya delta might increase the duration, severity or extent of hypoxia on the southwestern Louisiana shelf or the upper Texas coast.

Any discussion of nutrient management scenarios must be undertaken within another overall context--that of global climate change. A general circulation model by Miller and Russell (1992) predicted that runoff in freshwater would likely increase for 25 of the world's 33 largest rivers. Precipitation in the Mississippi River watershed is likely to increase 20 percent with a doubled CO_2 climate, and runoff is expected to increase in most months, particularly May through August. This response is likely to affect water column stability, surface water productivity, and oxygen cycling in the northern Gulf of Mexico.

Justic´ et al. (in press) applied a 20 percent increase in freshwater flux, primarily during the May-August period, to calculate an estimated average monthly runoff of the Mississippi River at Tarbert Landing compared to 1985–1992. The integrated doubled CO_2 runoff at Tarbert Landing will be around 0.5×10^{12} m^3 yr^{-1}. Assuming that the highest increase in runoff will occur during May, the maximum monthly runoff value for a doubled CO_2 climate will be approx. 4×10^4 m^3 s^{-1}. This result is substantially higher than the monthly maximum for the Great Flood of 1993 (3.2×10^4 m^3 s^{-1}). Surface salinity in the Gulf is likely to decrease substantially, and water column stability will increase. Manipulations of a physical-biological two-box model (Justic´ et al. in press) indicated that there will be a 30-60 percent decrease in summertime subpycnoclinal oxygen content, relative to the 1985–1992 average. Under those conditions, the hypoxic zone in the northern Gulf of Mexico will probably expand and encompass an area greater than that of the summer of 1993.

Effects on Living Resources

Hypoxia may affect fisheries resources by direct mortality, altered migration, reduction in suitable habitat, increased susceptibility to predation (including by humans), changes in food resources and susceptibility of early life stages. Studies of benthic communities and demersal communities show distinct responses of various members of the communities to decreases in dissolved oxygen concentration (Rabalais and Harper in prep.). Oxygen deficiency stressed benthic communities are characterized by limited taxa (none with direct development, e.g., amphipods), characteristic resistant infauna (e.g., a few polychaetes and sipunculans), reduced species richness, severely reduced abundances (but never azoic), low biomass, and limited recovery following abatement of oxygen stress (Rabalais et al, 1993; 1995).

Summary

Hypoxia is a severe and dominant feature of the northern Gulf of Mexico, that is linked to the freshwater fluxes and nutrient loads of the Mississippi and Atchafalaya Rivers. River water quality has changed since the turn of the century and accelerated since the 1950s. The adjacent continental shelf ecosystem has responded by increased productivity, eutrophication, and oxygen stress. Solutions are warranted that are directed at nutrient reductions through management practices in the watershed.

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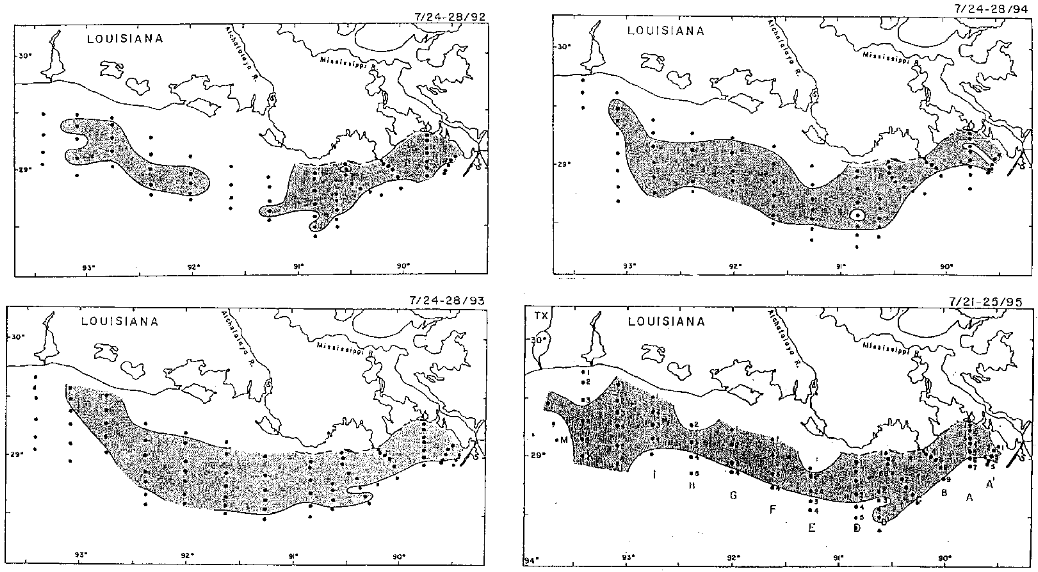

Figure 7.
Distribution of near-bottom water hypoxia (dissolved $O_2 \leq 2$ mg l^{-1}) i mid-summer for the dates indicated in 1992, 1993, 1994 and 1995. Data from hypoxia monitoring studies of N. N. Rabalais, R. E. Turner and W. J. Wiseman, Jr. (From Rabalais et al. in review.)

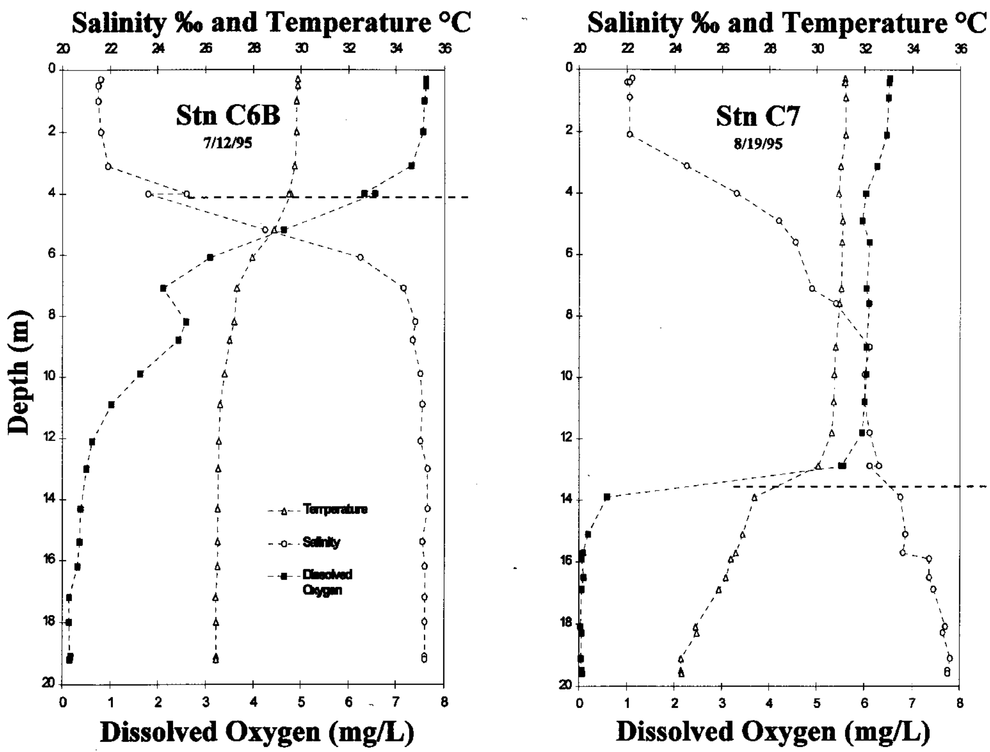

Figure 8.
Structure of water column for a salinity-controlled pycnocline and profile of dissolved oxygen (left panel) and a temperature-controlled pycnocline and profile of dissolved oxygen (right panel). Data from hypoxia monitoring studies of N. N. Rabalais, R. E. Turner and W. J. Wiseman, Jr.

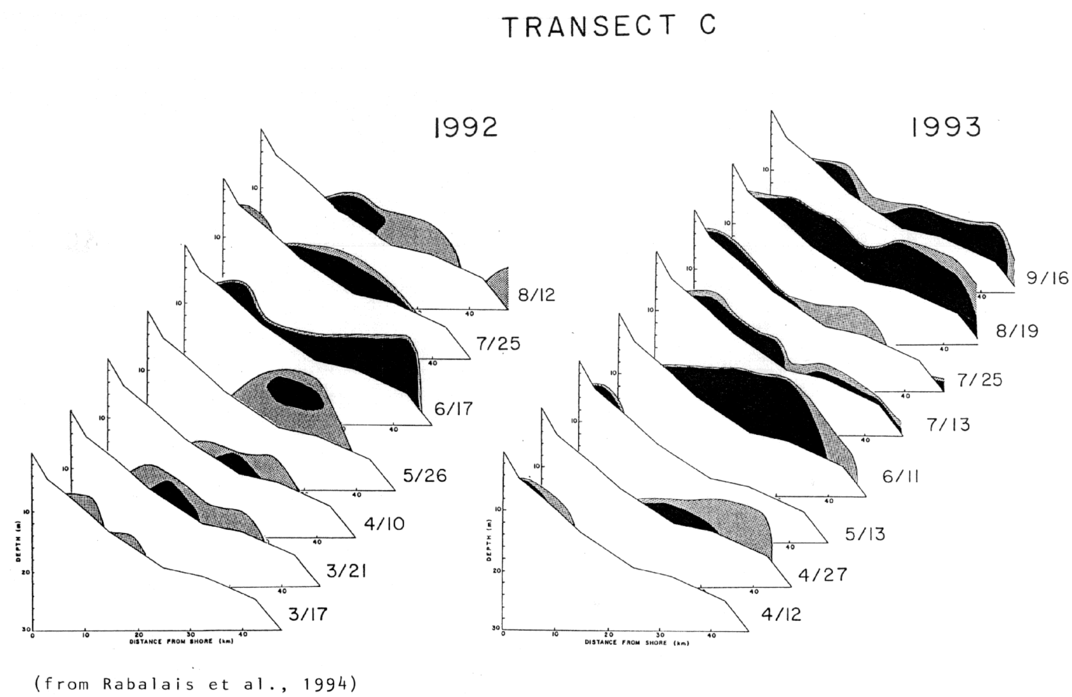

Figure 9.
Cross-section of southeastern Louisiana shelf showing seasonal progression and extent of bottom hypoxic zones during 1992 and 1993. Stippled area indicates < 2 mg l^{-1}; black areas indicate < 1 mg l^{-1}. (From Rabalais et al. 1994a.)

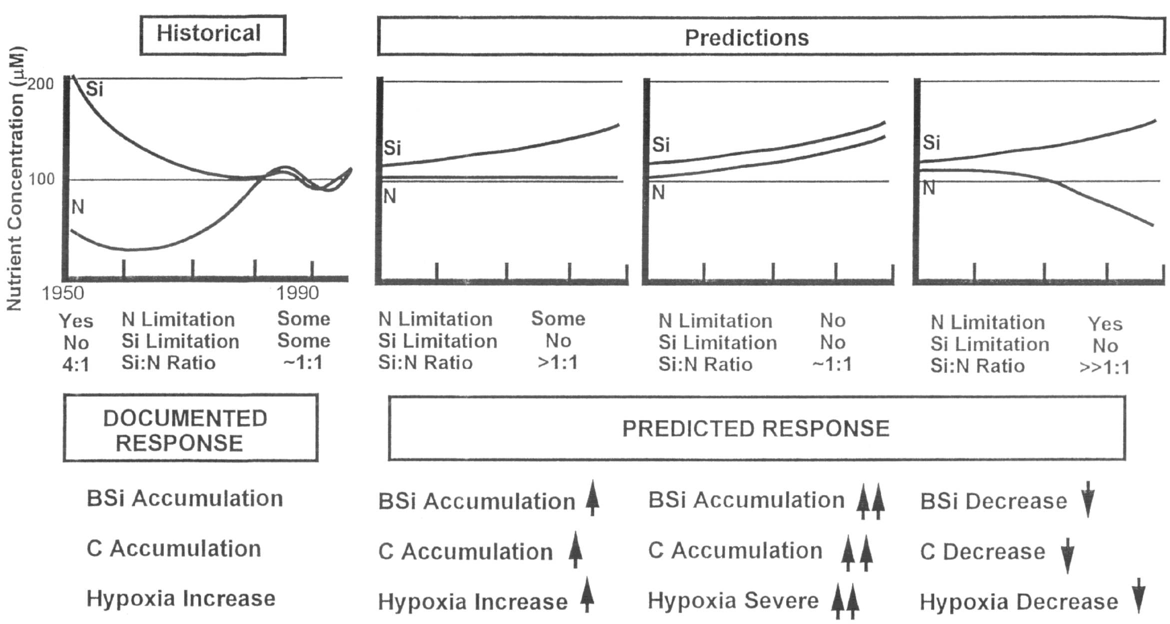

Figure 10.
A schematic of documented historical changes in riverine nutrient concentrations, nutrient ratios, and biological responses, and a series of predicted responses depending on a constant increase of silica and varying changes in nitrogen loadings. A stronger response is indicated by double arrows. (Modified from Rabalais et al. in press.)

Presentation Discussion

Nancy Rabalais *(Louisiana State University—Baton Rouge, LA)*

Alan Ballard *(Gulf of Mexico Program—Stennis Space Center, MS)* asked Nancy Rabalais what percentage of the Mississippi River outflow flows into the hypoxic area.

Nancy Rabalais responded by saying that William Wiseman addressed the amount of freshwater in the shelf and showed the seasonal progression of the freshwater in the area during his presentation. Most of the Atchafalaya River and 50 percent of the Mississippi River discharge water flow west.

Scott Dinnell *(USM Center for Marine Scienc—MS)* added that 10 percent of the total water content of the shelf (although it is seasonal) is freshwater.

Neil Armingeon *(Lake Pontchartrain Basin Foundation—Metairie, LA)* noted that Nancy Rabalais mentioned that one of the proposed river diversions would have little or no impact on the hypoxic zones in the Gulf. He then continued by asking her opinion on the impact that diversion would have on the quality and management of the receiving waters.

Nancy Rabalais responded by saying that she felt river diversions should be done to control freshwater and sediments, not as a panacea for the low oxygen conditions.

Mike Waldon *(USL—Lafayette, LA)* disputed that 48,000 csf is 10 percent of the average flow of the river. He said that the total average is approximately 450,000 cfs. Therefore, 48,000 csf is slightly more than 10 percent. He added that only some of the possible diversions were presented.

Nancy Rabalais agreed that there are other possible diversions. She had presented only those diversions for which she had data, and that most directly affected the southwestern shelf. She continued by saying that she had demonstrated the southwestern shelf down-plume from the Atchafalaya River also experiences extreme bouts of hypoxia and stressed that those areas compared statistically to the two-month time lag of peak river flow in the Atchafalaya River system.

An unidentified gentleman from the audience asked Nancy Rabalais if the growth of soybeans instead of the over application of fertilizer could be the primary contributor to the hypoxia problem since the sources of nutrients in the watershed were 50 percent from fertilizers, 30 percent of that being from leguminous crops.

Nancy Rabalais responded that there are many nutrient sources to the river. Those sources and the fate and transformation of those sources, as they move down the watershed, are not yet well understood.

Lon Strong *(U.S. Department of Agriculture/ Natural Resources Conservation Service—Jackson, MS)* asked if the sewage discharge data presented represented treated or untreated wastewater.

He also asked Nancy Rabalais to comment on her statement that sewage was not a significant source of input. Wastewater treatment discharges are continuous and the total nitrogen content in the effluent ranges between 2–60mg/L, compared to most run-off from cropland which is storm-event driven and lower in nitrogen content.

Nancy Rabalais responded by saying that she did not know all of the details of Bob

Howarth's paper but that Bob Howarth and his colleagues do not consider sewage an anthropogenic input to the system. She concluded by saying the budget presented was for annual inputs for the whole watershed.

Paul LaViolette *(Gulf Weather Corporation—Stennis Space Center, MS)* asked if other effects of modifying the flow of the river through the Atchafalya had been studied.

Nancy Rabalais replied that it was one of the management scenarios for coastal Louisiana.